development

SUPPRESSOR AND

FOR THE

L. R. Jordan and C. M. Auble, Douglas Aircraft Co., Inc.

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EARLY in the DC-8 program, our company undertook the development and design of a jet-noise suppressor and thrust brake for the DC-8 airplane. A summary of this work is presented herein.

Although the exact requirements of a jet-noise suppressor have not been established, it has long been known that large jet transports would require noise suppression in airline service. Early in the development program it was estimated that a 9–12 db suppressor could be developed for the DC-8. When considered from a sound energy standpoint, this meant about a 90% reduction in energy. Obviously, the solution to the problem was not a simple one.

In addition to the noise problem, it was felt that aerodynamic braking after touchdown would be required by high-speed jet transports, as has been the case with piston-engine aircraft. An added advantage was anticipated in the use of an aerodynamic braking device in flight. Accordingly, thrust braking was considered a requirement for the airplane. A braking force equivalent to that obtained

THIS PAPER presents the development of the DC-8 suppressor and thrust brake unit from initial test work through the final design. The selection of the production unit was based on a wide background of test work using both model and full-scale facilities. On the basis of this work, the configuration selected for production consisted of a fixed, corrugated, suppressing nozzle with a retractable ejector. A target-type thrust brake, mounted in the ejector, was chosen for the thrust brake production unit. Approximately 12-db suppression and 44% reverse thrust are provided by the unit.

The ejector is hydraulically operated and the thrust brake air actuated. Both actuation systems obtain power from the aircraft systems which provides for operation during engine-out conditions. Alternate methods of actuation are provided in case of a primary system failure.

Mechanically, the suppressor-thrust brake was designed to provide high reliability and to be capable of operation anywhere within the flight envelope of the airplane. Particular attention was given to component failures and their effect on safety of the unit.

of the

THRUST BRAKE

DC-8 AIRPLANE

with reversing propellers on present-day aircraft was considered the minimum requirement for landing. Consequently, reversed thrust equal to approximately 40% forward gross thrust at maximum continuous power setting became the target for the DC-8. The DC-8 suppressor and thrust brake development goal thus became: (1) jet noise suppression of 9–12 db, and (2) at least 40% thrust in reverse. This goal was to be accomplished with a minimum penalty to thrust, drag, and specific fuel consumption during take-off and cruise.

In view of the lack of theoretical methods of analysis for either suppressors or thrust brakes, selection of a design configuration was based on a wide background of test work. This test work was accomplished on both model and full-scale test facilities, utilizing 10%, 20%, and full-scale models. In addition, wind tunnel tests were conducted using 6.87% scale models.

The final design was selected on the basis of test results with some compromises being necessary to:

1. Obtain the best balance between sound reduction, thrust loss, drag, and thrust braking performance.
2. Make an installation compatible with our reliability and safety standards.

Development Test Program

The test program was started in 1955, using the 10% scale static test facility. The following year, the 20% scale facility shown in Fig. 1 became available and has since been used for all static model test work. Full-scale test work was first carried on with the help of Pratt and Whitney and NACA at their respective facilities. In 1957, the Douglas full-scale test stand shown in Fig. 2 became operational. Wind tunnel thrust and drag tests were conducted in the United Aircraft high-speed wind tunnel with 6.87% scale models. These tests were conducted

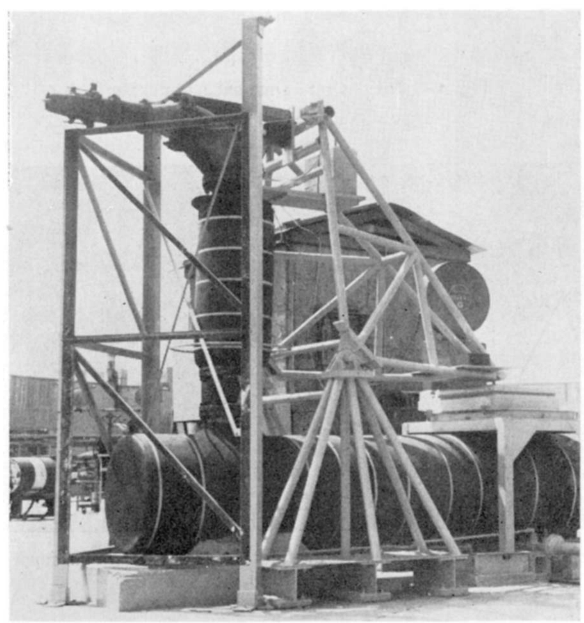

Fig. 1 — Douglas Santa Monica 20% scale test facility

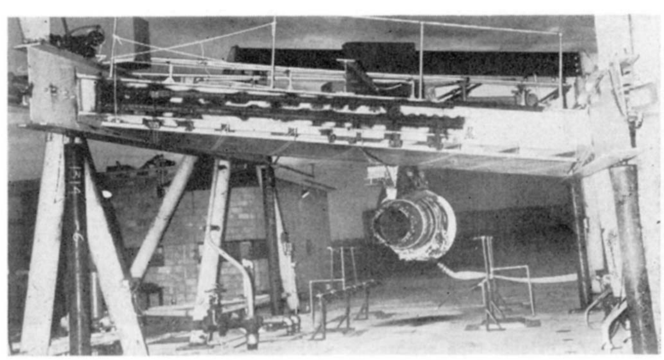

Fig. 2 — Douglas full-scale test facility

over a wide range of exhaust nozzle pressure ratios and aircraft speeds.

Sound suppression characteristics of suppressing nozzles were evaluated by observing overall sound pressure levels at a given radius from the nozzle. The data were plotted versus jet velocity to indicate sound levels at various power settings. This noise level, when subtracted from that of a reference nozzle (convergent bulleted nozzle), tested under identical conditions, afforded a measure of the suppressor's acoustic effectiveness. The curves in this paper present sound reduction at an angle of 30 deg to the jet axis. In most cases, this was the angle of maximum sound pressure level.

Thrust performance of a suppressing nozzle was also compared to that of a reference nozzle. Suppressor thrust loss was defined as the per cent loss in specific thrust (thrust per unit gas flow) with respect to the reference nozzle operating at the same pressure ratio and temperature. The thrust minus drag characteristics of a given nozzle and its nacelle fairing were evaluated in the wind tunnel. These data were compared to those of the reference nozzle on a specific thrust basis. In all cases a convergent, bulleted nozzle design was used as the reference. This reference nozzle is shown in Fig. 3. It is similar in many respects to that recommended by the engine manufacturer for installations where sound suppression is not required. In all test work, both the reference and suppressing nozzles were tested over as wide a range of exhaust nozzle pressure ratios as possible.

In thrust brake tests, the amount of reverse thrust was compared to the forward thrust of the reference nozzle operating at the same pressure ratio. The effect of the thrust brake on engine airflow was noted in all tests. Thrust brake stability characteristics were visually observed. All models which showed promise for final designs were tested for actuating and linkage loads over a wide range of nozzle conditions. These tests were accomplished under both static and simulated flight conditions wherever possible.

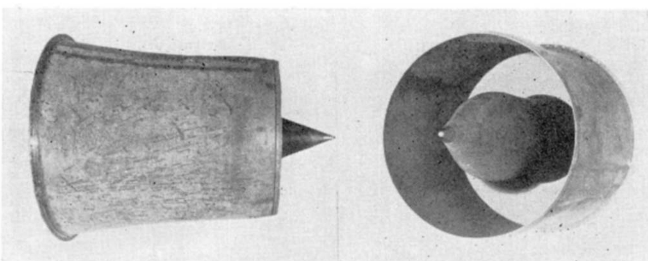

Fig. 3 — Douglas reference exhaust nozzle

Selection of Design Configuration

Selection of Suppressor Design — In the test program, two basic types of suppressing nozzles were studied simultaneously. These were adjustable and fixed types. Both types were tested with and without a retractable ejector. It was found early in the program that, if an ejector were to be used, retraction would be necessary because of the performance

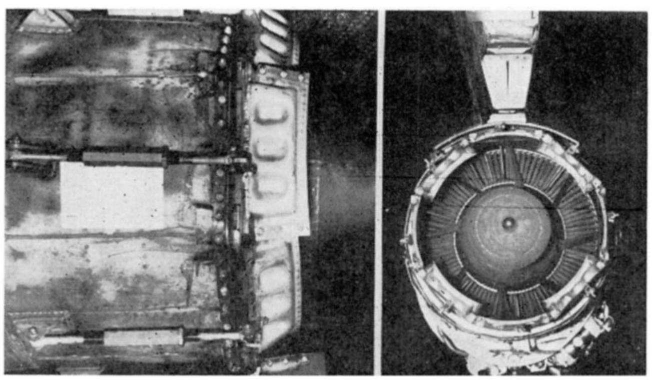

Fig. 4 — Adjustable-type suppressing nozzle (flaps shown in suppressing position)

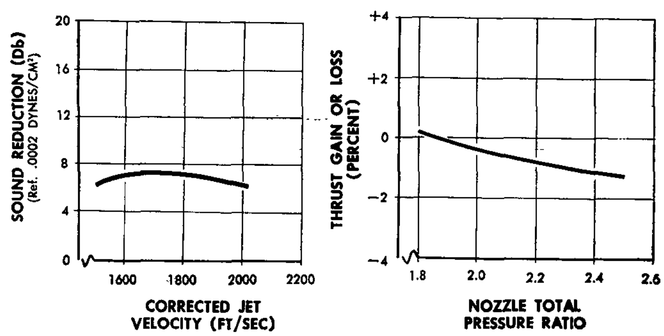

Fig. 5 — Sound and thrust performance of adjustable suppressing nozzle

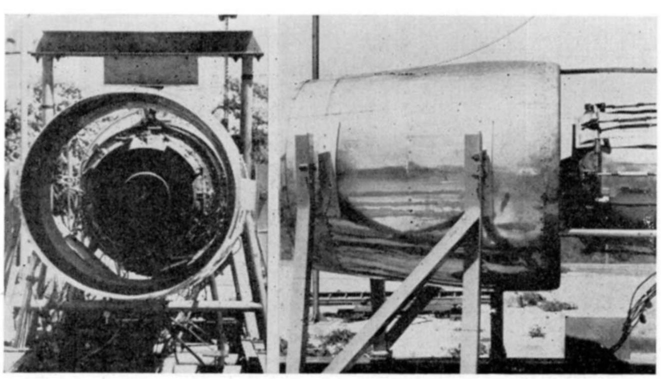

Fig. 6 — Adjustable-type suppressor with ejector (flaps shown in suppressing position)

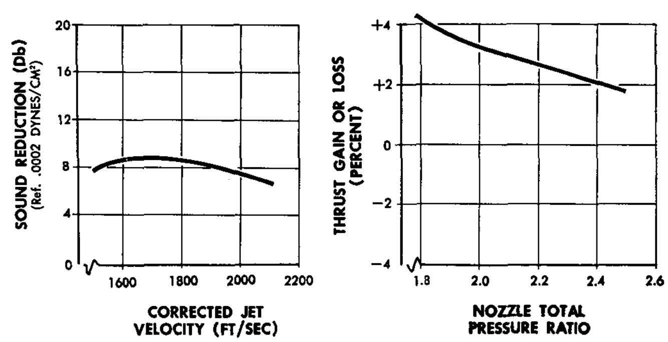

Fig. 7 — Sound and thrust performance of adjustable suppressing nozzle with ejector

loss at cruise in the extended position.

A typical adjustable suppressing nozzle is shown in Fig. 4. It is fitted with flaps which form a simple convergent cone in the retracted position. The flaps are hinged about 4 in. forward of the nozzle exit plane. In the suppressing position, alternate flaps are rotated in the direction of and away from the thrust axis, respectively. Thus, although the effective nozzle area is not changed, the exit has a castellated appearance. Sound reduction and thrust loss characteristics of this nozzle are shown in Fig. 5. The nozzle fell short of the sound reduction goal, although a relatively small thrust loss was incurred over most of the operating range. Fig. 6 shows this nozzle with an ejector. The addition of an ejector improved sound and static thrust performance, as can be seen in Fig. 7. However, the noise suppression was still considered to be inadequate.

Many different models of this nozzle and other adjustable types were tested. It became apparent during the course of the test work that much development effort would be required before adjustable suppressing nozzles could be designed to give the desired performance. In addition to the performance problem, it was anticipated that many reliability and safety problems would result from a design which placed moving parts continuously in the hot exhaust gases. Therefore, adjustable suppressing nozzles were abandoned in favor of fixed suppressing nozzle configurations.

Two types of fixed nozzles were tested: the multitube and corrugated types, respectively. A typical multitube nozzle is shown in Fig. 8. This particular nozzle was originally designed by Rolls-Royce and is temporarily in use on the first DC-8 test airplane. As shown in Fig. 9, the acoustic performance of this nozzle is much better than that of the adjustable type.

A typical corrugated nozzle and its performance is shown in Figs. 10 and 11, respectively. Corrugated

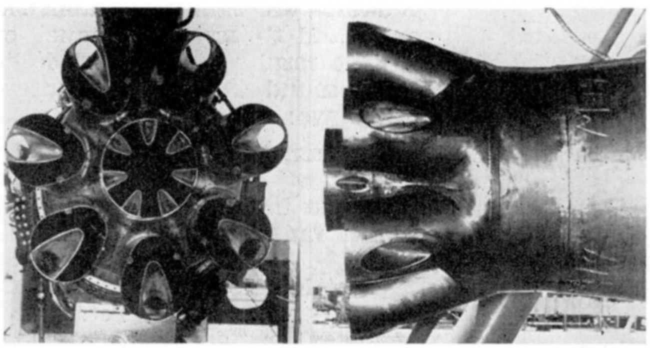

Fig. 8 — Fixed multitube-type suppressing nozzle

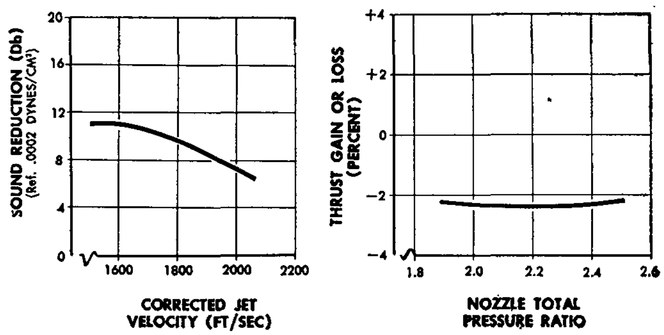

Fig. 9 — Sound and thrust performance of multitube suppressing nozzle

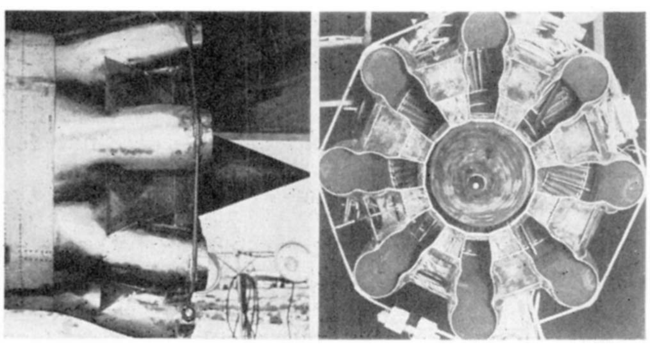

Fig. 10 — Fixed corrugated-type suppressing nozzle

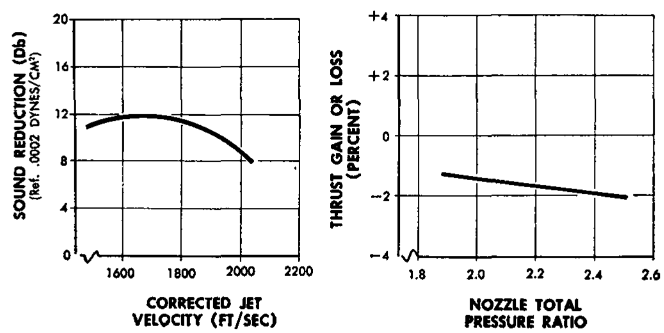

Fig. 11 — Sound and thrust perfromance of corrugated suppressing nozzle

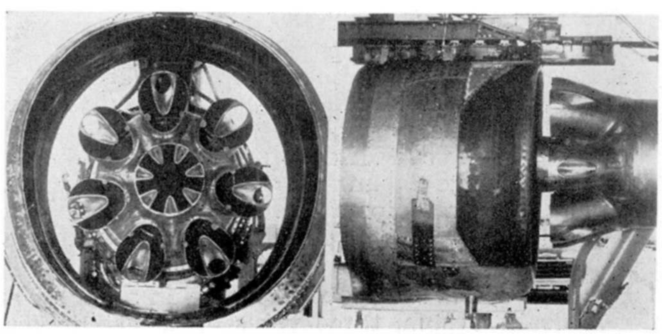

Fig. 12 — Fixed multitube-type suppressor with ejector

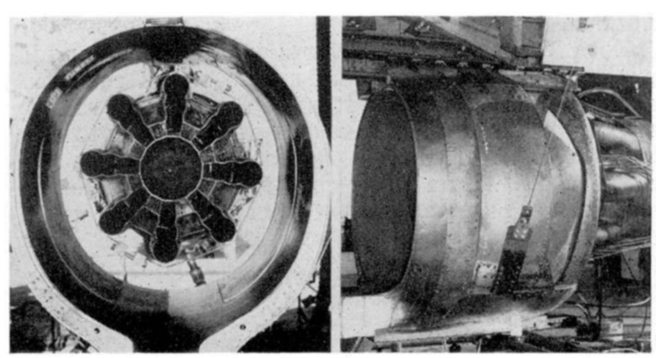

Fig. 13 — Fixed corrugated-type suppressor with ejector

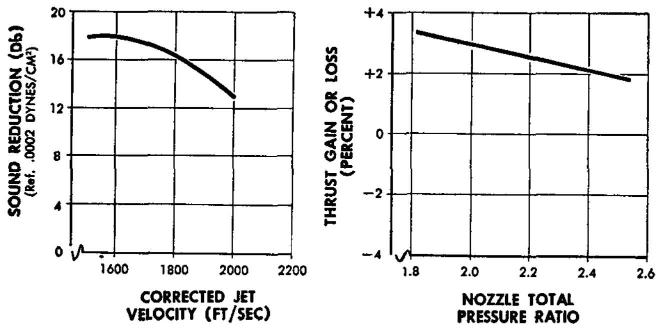

Fig. 14 — Sound and thrust performance of multitube suppressing nozzle with ejector

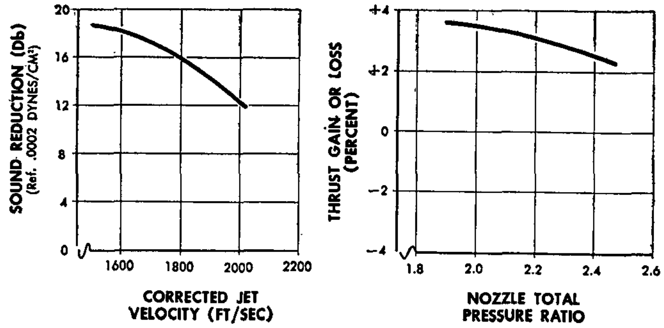

Fig. 15 — Sound and thrust performance of corrugated suppressing nozzle with ejector

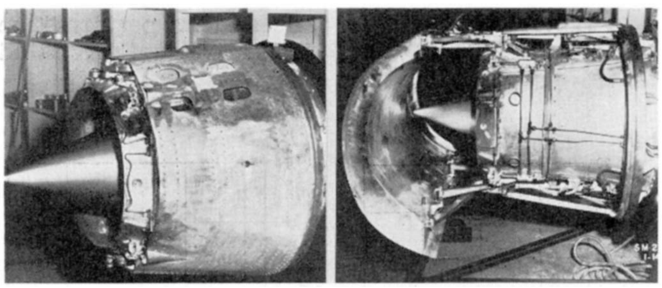

Fig. 16 — Adjustable-type suppressor with thrust brake in forward and braking positions

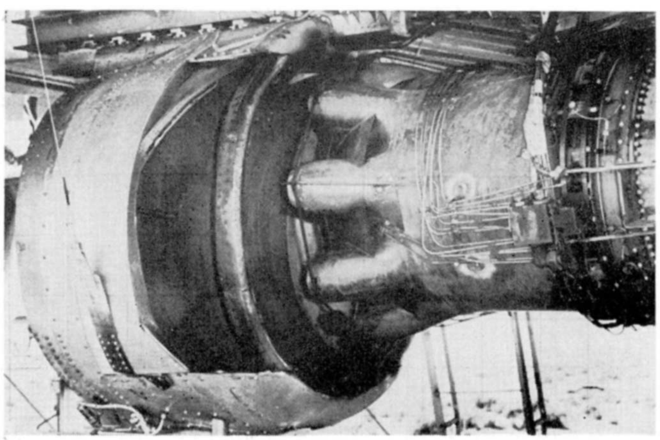

Fig. 17 — Fixed corrugated-type suppressor with ejector thrust brake

types show sound suppression and thrust loss characteristics similar to those of the multitube nozzle.

Both fixed types of nozzles showed promise as suppressors but did not produce the sound reduction desired. The addition of an ejector improved the sound performance of both types sufficiently to meet the design objective. In addition, the ejector augmented the thrust sufficiently to offset the supressor thrust loss for take-off operation. The multitube and corrugated nozzles with an ejector added are shown in Figs. 12 and 13, respectively. Fig. 14 shows sound reduction and static thrust performance of the multitube nozzle with an ejector. Similar curves for the corrugated nozzle are shown in Fig. 15. As can be seen in the figures, both nozzle types give comparable sound reduction and thrust performance with an ejector. For final design, the corrugated type was chosen because wind tunnel tests showed it had less drag than the multitube type.

To provide design data, a program was established to optimize the sound and thrust performance of corrugated nozzles. The results of this work indicated that for optimum sound reduction characteristics a nozzle should have:

1. As large an outer diameter as possible at the exit plane.
2. Lobes which increase in cross-sectional area at the exit plane with radial distance from the thrust axis.
3. No fewer than eight lobes.
4. A relatively small center body or bullet.
5. At least 90% of the exhaust area distributed in the lobes. In other words, less than 10% of the exhaust area should be located in the annular passage near the bullet.

For minimum thrust loss, it was found that:

1. The nozzle should have a cross-sectional flow area that is constant or slightly converging over most of its length. Convergence to the final flow area should take place rapidly in the final few inches of gas travel.
2. The fewer the number of lobes, the less the thrust loss.
3. Center body or bullet size has little effect on static thrust of the nozzle.

In designing the ejector, the geometry was largely determined by installation considerations. However, tests were made which indicated that in installations where some design latitude is available, optimum sound and/or thrust performance is obtained when the ejector:

1. Is made as long as possible.
2. Internal lines are smooth and unbroken.
3. Exit diameter is equal to or slightly greater than the outer diameter of the nozzle.
4. Is as nearly cylindrical as possible.
5. Leading edge thickness is sufficient to eliminate separation in static operation.
6. Leading edge is placed slightly aft of the nozzle exit plane.

Selection of Thrust Brake Design — In selecting a thrust brake design, three types of thrust brakes were considered. These were the internal cascade,

external target, and target-type mounted in the ejector. The internal cascade consisted of turning vanes mounted in the tailpipe with doors which block the tailpipe in the braking configuration. The target type consisted of contoured doors which mount behind the exhaust nozzle in the braking position. Early in the program a decision was made to use the target rather than the cascade type for the following reasons:

1. The internal cascade thrust brake requires a gas seal between the tailpipe and the nacelle. It was anticipated that this seal would present a formidable design problem, with some leakage in service being unavoidable. This leakage would result in a thrust loss not experienced by the target-type thrust brake.
2. The target-type thrust brake is isolated from the engine by a nozzle which is choked when reverse thrust is applied, and thus should have negligible effect on engine operation.
3. The internal cascade thrust brake requires that moving parts be placed continuously in the hot gas stream. Furthermore, its position makes accessibility difficult. Maintenance problems were expected to be more frequent and difficult than with a target-type thrust brake.

As a result of this decision, a minimum of test work was carried out on cascade-type thrust brakes.

The external target-type thrust brake was tested only in combination with adjustable-type suppressing nozzles. A typical installation is shown in Fig. 16. This type of thrust brake was found to provide acceptable performance from the standpoints of reverse thrust, engine operation, and stability. However, with the decision to use an ejector in the final suppressor design, integration of the thrust brake with the ejector was considered desirable in the interest of both simplicity and weight.

A typical ejector thrust brake installation is shown in Fig. 17. Two thrust brake buckets rotate so as to close off the ejector completely in the braking configuration. In the forward thrust position, the bucket surfaces form the inner liner of the forward ejector wall. A cross-section of the ejector center section is shown in the thrust braking position in Fig. 18. The following design criteria were established during the test work on this type of thrust brake:

1. Moderate aft sweep (Fig. 18) on the buckets in the braking position has little effect on the reverse thrust. Aft sweep was found to be desirable to stabilize the gas flow during the braking operation.
2. One per cent of unblocked area in the ejector results in approximately 2% loss in braking thrust.
3. The length of the aft lip extension which serves to turn the flow in a forward direction (Fig. 18), has a relatively small effect on performance. The optimum length was found to be approximately one-third of the reference nozzle diameter.
4. Corrugated nozzles with large center bodies produce less reverse thrust than corrugated nozzles with small center bodies.
5. The ejector leading edge shape and geometry has little effect on reverse thrust.
6. The per cent of reverse thrust is relatively insensitive to power setting under static operating conditions.
7. This type of thrust brake has negligible effect on engine operation.

The performance of this thrust brake installation in an ejector is shown in Fig. 19. The curve shows that the reverse thrust decreases slightly as nozzle pressure ratio decreases. The airflow curve in Fig. 19 indicates that the thrust brake has negligible effect on engine operation over the entire operating range.

Design, Operation, and Safety Features of Production Suppressor-Thrust Brake

Production Suppressing Nozzle — A photograph of the production suppressing nozzle is shown in Fig. 20. The nozzle design requirements were established

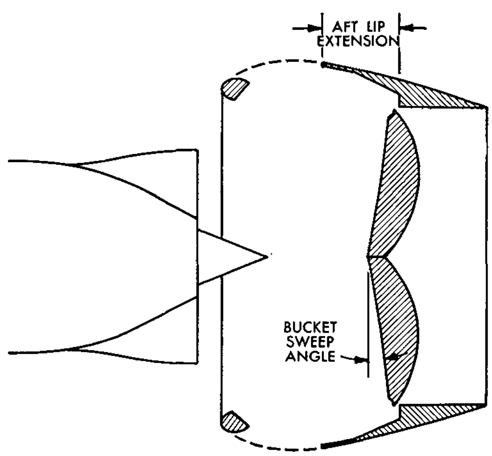

Fig. 18 — Cross-section of ejector thrust brake

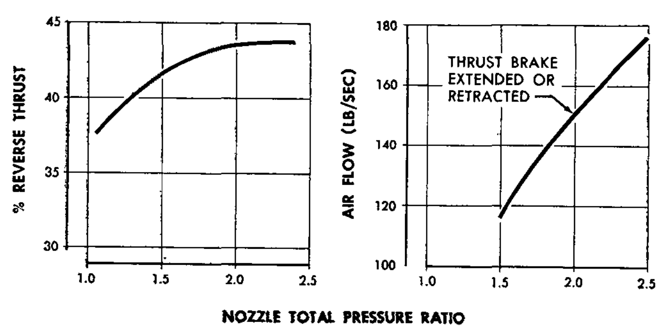

Fig. 19 — Reverse thrust and airflow performance of ejector thrust brake

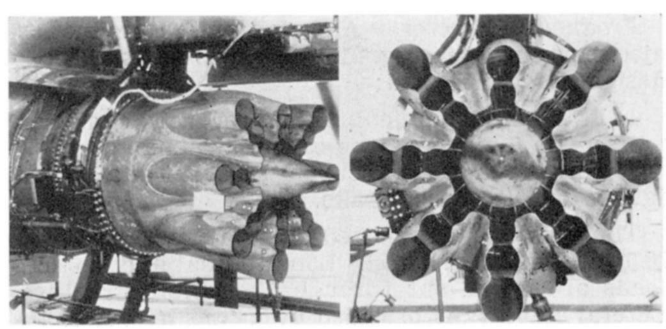

Fig. 20 — DC-8 production suppressing nozzle

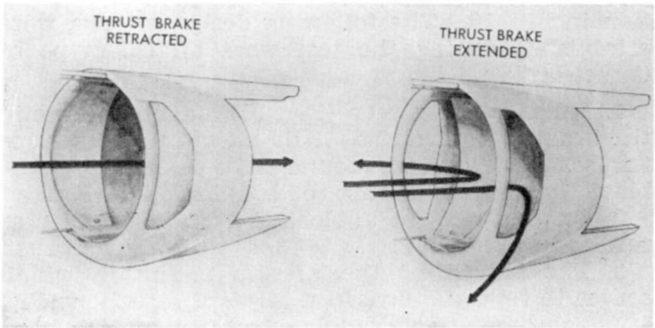

Fig. 21 — DC-8 production ejector and thrust brake

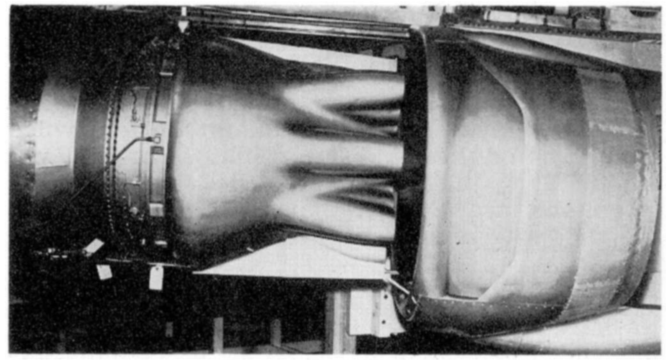

Fig. 23 — Mockup of production suppressor-thrust brake (ejector fully extended)

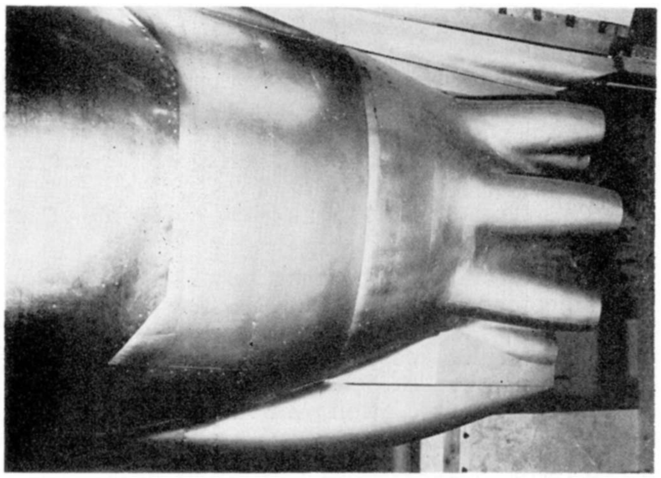

Fig. 22 — Mockup of production suppressor-thrust brake (ejector retracted)

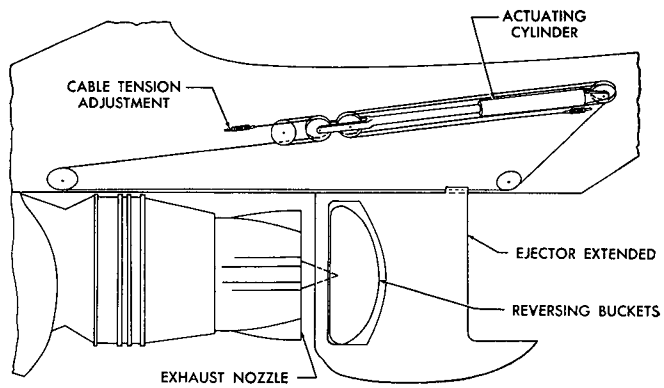

Fig. 24 — Schematic of ejector actuating mechanism

as: (1) high reliability, and (2) good dimensional stability.

To meet these requirements, the nozzle was designed to have negligible distortion due to temperature and pressure under service conditions. This was accomplished with a "triple bubble" design incorporating internal vanes and radial struts to place stress-carrying material in tension. Construction is of welded 19-9 DL stainless steel. Relatively light sheet is used for the outer portion of each lobe. Heavier material is used in the "valley" between the lobes. Radial struts, welded to the heavier material and bolted to a ring inside the bullet fairing, are used to retain the corrugated shape. The top lobe is reduced in height to eliminate washing of exhaust gas over the pylon. Nozzle area adjustment is provided by means of an adjustable bullet cone.

Production Ejector — A sketch of the production ejector is shown in Fig. 21. The ejector structure is designed to withstand:

1. Full aerodynamic braking for any condition within the flight envelope of the airplane.
2. Forces which may ocur in the event of a bucket failure in the thrust brake.

The ejector is supported from a track mounted below the pylon firewall. Longitudinal and vertical loads are taken out through the pylon structure. Lateral stability is provided by means of a link attached to the lower leading edge of the ejector. This link rides a lower track supported from the engine and nozzle. The highly stressed structural members are heat-treated 17-7 PH stainless steel. The balance of the ejector is constructed of 19-9 DL stainless steel. The inner skins on both the thrust brake buckets and the aft portion of the ejector are slip-joint supported to allow for differential thermal expansion.

Photographs of the installation mockup are shown in Figs. 22 and 23 for the retracted and extended positions, respectively. In the retracted position, the forward portion of the ejector including the thrust brake openings is covered by the engine access doors. A fixed cowl completes the aft nacelle fairing. The fairing on the underside of the ejector houses the thrust brake actuator and linkage.

A sketch of the ejector actuation system is shown in Fig. 24. The ejector rides on two sliding carriage assemblies and is positioned fore and aft along the pylon track by a 5/16-in. steel cable. Power is supplied through a piston operated by the aircraft hydraulic system. The actuator extends the ejector in 3 sec and retracts it in 6 sec. The ejector is held in either position by locking hydraulic fluid in the cylinder. Provisions are made for adjusting cable tension, cylinder stroke, and ejector position. Two bayonet-type disconnect valves are fitted in the aft slide assembly. When the ejector is fully extended, these connect with valves in the pylon at the rear of the ejector track and thus supply air for the thrust brake actuator. A shock absorber is installed

in the aft track assembly at the ejector stop to absorb impact energy in case of an actuating system failure. Latches are provided on the pylon track to prevent inadvertent extension in flight.

Emergency actuation is possible in case of a hydraulic system failure by means of stored high-pressure air. Air capacity is provided for one extension or retraction of each ejector. The system is cable operated from the cockpit.

A positive cam mechanism is incorporated which precludes ejector retraction with thrust brake buckets extended. This mechanism retracts the buckets as the ejector is pulled forward by means of cam action between the upper bucket pivots and the track. This system operates only in the event of failure in the thrust brake actuating system.

The ejectors are operated by two overhead switches in the cockpit. One switch operates both outboard ejectors, the other the inboard units. These switches energize solenoid valves which port hydraulic fluid to the actuating cylinders. Lights in the cockpit indicate full extension.

Production Thrust Brake — The thrust brake buckets and their actuating system are shown schematically in Fig. 25. They are mounted on stainless-steel shafts which rotate in self-aligning bearings attached to shear plates at the top and bottom of the ejector. The thrust brake pivot axes are located outboard of the bucket center of pressure. This location provides for bucket retraction by jet forces in case of an actuator power failure.

The buckets are actuated by a pneumatic piston and cylinder mounted at the bottom of the ejector. As shown in Fig. 25, the piston is connected to the bucket lower pivots through a bell crank linkage system. This system operates the buckets in 1–2 sec. Air is supplied to the thrust brake actuator through the bayonet valves previously mentioned. Thus, the thrust-brake may not be actuated until the ejector is fully extended, since high-pressure air is not otherwise available. The air used for actuation is taken from either the aircraft pneumatic manifold or the engine high-pressure bleed system. This system allows reverser bucket actuation on any engine, whether or not the engine is in operation. In the event of a thrust brake pneumatic system failure, the thrust brake buckets may be retracted by retracting the ejector, in the event they have not previously been faired due to pressure loading.

Since the thrust brake cannot operate until the ejector is fully extended, provision has been made to extend the ejector automatically when thrust braking is selected. This is accomplished by pressure switches which energize the ejector solenoid valves when the thrust brake pneumatic supply line becomes pressurized.

At the present time, no thrust brake bucket position modulation is provided. The thrust brake must be in either the full-open or full-closed position. Variation of reverse thrust is accomplished by throttle setting.

Thrust brake operation from the cockpit is controlled by the thrust brake throttles which are pivoted from the main throttles. Operation of the reverse throttle is possible only when the main throttles are in the idle position. Selection of thrust braking directs engine bleed air to the actuating cylinder. This is accomplished through an engine mounted pilot valve which takes its signal from a cam on the engine throttle shaft. The thrust brake actuating valve is a slide-type valve allowing pressurization on either side of the piston. Thus, normally the thrust brake buckets are retracted by the actuating piston when forward thrust is selected. A cockpit light indicates full-braking bucket position.

Both the thrust brake and ejector are operable from the normal ground power plugs. Thus, engine operation is not necessary for ground check-out.

Summary and Conclusions

Design features of the DC-8 suppressor thrust brake configuration can best be seen in the exploded assembly sketch shown in Fig. 26. The design consists of a fixed, corrugated-type nozzle with a retractable ejector. The target-type thrust brake is mounted in the ejector. This design, which is the culmination of test work on many suppressor and thrust brake configurations, meets or exceeds the performance objectives originally set up in the development program. Work is continuing at Douglas, however, to improve both thrust and sound suppression performance of the suppressor-thrust brake unit.

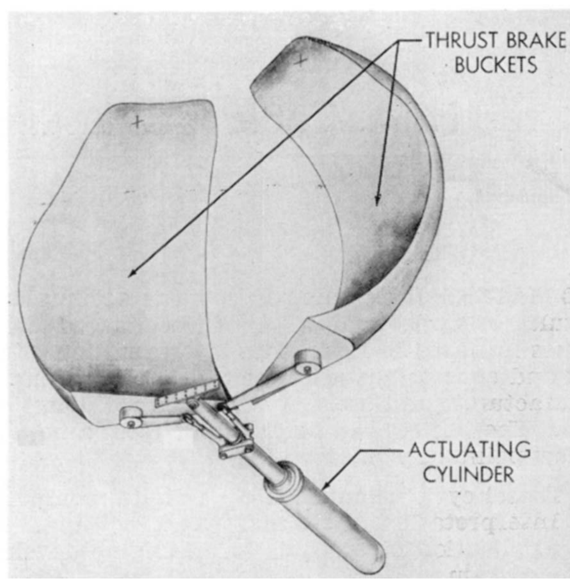

Fig. 25 — Thrust brake actuating system (thrust brake partially extended)

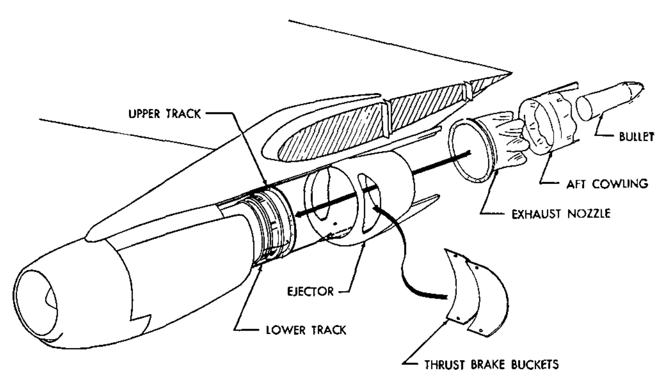

Fig. 26 — Exploded view of suppressor-thrust brake assembly